Pronounced long term flux variability of the Anomalous X–ray Pulsar 1E 1048.1−5937

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ABSTRACT

We present *XMM-Newton* and *Chandra* observations of 1E 1048.1−5937 , being the first to show evidence for a significant variation in the X-ray luminosity of this Anomalous X–ray Pulsar (AXP). While during the first *XMM-Newton* (2000 December) and *Chandra* (2001 July) observations the source had a flux consistent with that measured on previous occasions ($\sim 5\times10^{-12}$ erg cm^{-2} s^{-1}), two more recent observations found it at a considerably higher flux level of 2×10^{-11} erg cm^{-2} s^{-1} (2002 August; *Chandra*) and 10^{-11} erg cm^{-2} s^{-1} (2003 June; *XMM-Newton*). All the spectra are fit by the sum of a blackbody with kT$\sim$0.6 keV and a power law with photon index $\sim$3. No significant changes were seen in the spectral parameters, while the pulsed fraction in the 0.6-10 keV energy range decreased from $\sim$90% in 2000 to $\sim$53% in 2003. The spectral invariance does not support the presence of two physically distinct components in the AXP emission. The sparse coverage of the data does not permit us to unambiguously relate the observed variations to the two bursts seen from this source in the fall of 2001.

Subject headings: Stars: neutron; X–ray: stars;

1. Introduction

The Anomalous X-ray Pulsars (AXPs) are a small group of pulsars with a rotational period of a few seconds, a fairly stable spin-down and a very soft X–ray spectrum (Mereghetti & Stella 1995; van Paradijs, Taam & van den Heuvel 1995). If they are neutron stars, as their short spin period suggests, the loss of rotational energy inferred from the observed period and period derivative values is too small to power their luminosity of 10^{34}-10^{36} erg s^{-1}. AXPs are peculiar because of the strong evidence, accumulated over several years of intense observational effort, that they lack a main-sequence or giant mass-donor companion star (see Mereghetti et al. 2002 for a review). This has led to two classes of models involving isolated neutron stars. In the first class, the emission originates from accretion of material supplied by a residual disk (e.g., Ghosh, Angelini & White 1997; Chatterjee, Hernquist & Narayan 2000; Alpar 2001), while in the "*Magnetar*" model the energy source is the decay of an extremely high (10^{14}–10^{15} G) magnetic field (Duncan & Thompson 1992; Thompson & Duncan 1995, 1996). The latter model can explain the properties of the Soft Gamma-ray Repeaters (SGRs, see Hurley 2000 for a review), a class of bursting hard X–ray sources with quiescent soft X–ray emission quite similar to that of the AXPs. The magnetar interpretation has been supported by the recent discovery of short bursts in two AXPs, 1E 2259+586 (Kaspi et al. 2003) and 1E 1048.1−5937 (Gavriil, Kaspi & Woods 2002).

1E 1048.1−5937 was serendipitously diecovered with the *Einstein Observatory* as a 6.4 s pulsar near the Carina Nebula (Seward, Charles & Smale 1986) and is one of the best studied AXPs. Early observations with EXOSAT and GINGA indicated an unusually soft (compared to accreting binary pulsars) power law spectrum and measured a spin-down at a rate of $\sim 1.5\times10^{-11}$ s s^{-1} (Seward et al. 1986; Corbet & Day 1990). Higher quality spectra, not affected by contamination from bright nearby sources, could be obtained with the imaging instruments on board *BeppoSAX* (Oosterbroek et al. 1998), *ASCA* (Paul et al. 2000), and *XMM-Newton* (Tiengo et al. 2002). These data showed a two component spectrum, composed of a blackbody with temperature kT$\sim$0.64 keV plus a power law with photon index α_{ph} $\sim$2-3, and a 2-10 keV luminosity of $(1–2)\times10^{34}$ erg s^{-1} (for an assumed distance d=5 kpc). The source lies at low galactic latitude, resulting in a significant absorption in soft X-rays ($N_H \sim 10^{22}$ cm^{-2}).

Deviations from a constant spin-down rate were first observed with ROSAT (Mereghetti 1995). Long term monitoring with *Rossi-XTE* carried out since 1996 (Kaspi et al. 2001) has shown that, compared to other AXPs for which phase coherent timing could be obtained over

extended time intervals, 1E 1048.1−5937 is characterized by a relatively high level of timing noise. The *Rossi-XTE* observations were also used to search for long term flux variability. Unfortunately, the presence of other X–ray sources in the field of view[1] and the uncertainties in the subtraction of the time variable background, permitted us to use these data only to measure the pulsed component of the flux. Kaspi et al. (2001) concluded that the pulsed flux did not vary by more than 25% in 1996–2000.[2]

On the other hand, *Rossi-XTE* detected two bursts of short duration (about 51 and 2 s respectively) from the direction of 1E 1048.1−5937 on 2001 October 29 and November 14 (Gavriil et al 2002). Although the possibility that they originated from a different source within the instrument field of view cannot be completely excluded, it is likely that they were due to 1E 1048.1−5937 , especially in light of the detection of short bursting activity also in another AXP (1E 2259+586 , Kaspi et al. 2003).

Here we present *XMM-Newton* and *Chandra* observations showing significant long-term variability in the X–ray flux from 1E 1048.1−5937 .

2. Data analysis and results

2.1. *XMM-Newton*

1E 1048.1−5937 was observed with *XMM-Newton* on 2003 June 16 for about 19 hours. Here we report on the results obtained with the EPIC instrument, consisting of two MOS and one PN CCD cameras (Turner et al. 2001, Struder et al. 2001). After standard data cleaning to remove time intervals with high particle background, we obtained a net integration time of 47,000 s in the two MOS cameras, which were operated in Small Window mode (frame integration time of 0.3 s). The net exposure was 43,000 s in the PN camera, which was operated in the standard Full Frame mode with a frame integration time of 73 ms. The medium thickness filter was used in all cameras.

The data reduction was performed using version 5.4.1 of the *XMM-Newton* Science Analysis System. All the spectra described below were extracted in the 0.6-10 keV range and rebinned to have at least 30 counts in each energy bin. Background spectra were extracted from source free regions in the same CCD chips in which the source was detected.

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[1] in particular the highly variable source η Carinae lies at $\sim$40 arcmin

[2] As noted by the same authors, this does not exclude flux variations, provided that the pulsed fraction was anticorrelated with the phase-averaged flux in order to cancel out variations in the pulsed flux.

1E 1048.1−5937 had a net count rate of 3.3 counts s^{-1} in the PN camera, more than twice the value measured in a short *XMM-Newton* observation of 2000 December (Tiengo et al. 2002). For bright sources, the presence of more than one photon per pixel per frame time could affect the spectral results. Therefore, we checked for the possible presence of photon pile-up by comparing the spectrum extracted from a circular region around the source with that obtained excluding from the same region the central part (10″ radius) where pile-up is expected to occur. Since we found that the difference in the derived spectral parameters was within their statistical uncertainties, in the subsequent analysis we used a circular extraction region of radius 30″. The negligible pile-up in our observation is also confirmed by the fact that the MOS spectra, which do not suffer from this effect, gave results fully consistent with the PN spectra (see below).

Single component spectral models (power law, thermal bremsstrahlung and blackbody) did not provide acceptable fits, while good results were obtained with the "canonical" AXP model consisting of the sum of a blackbody and a power law. The best fit parameters (blackbody temperature kT$\sim$0.65 keV, photon index α_{ph} $\sim$3.3, absorption $N_H \sim 1.1 \times 10^{22}$ cm^{-2}) are similar to those measured on other occasions from this AXP.

We performed a similar analysis with the two MOS detectors, using only pattern 0 events. Since the results were fully consistent with those obtained with the PN camera, we finally made a joint spectral analysis of the three data sets. The corresponding best fit parameters are given in Table 1, where we also show the results of a re-analysis, with the updated software and calibrations, of the 2000 December data. A comparison of these values clearly shows that, while the luminosity of 1E 1048.1−5937 increased by a factor of two, its spectrum remained virtually unchanged. The ratio of the fluxes in the two spectral components is, within the errors, consistent with a constant value.

The source pulsations at 6.4 s were easily detected in the 2003 EPIC data. After correcting the PN times to the Solar System Barycenter, a standard timing analysis based on folding and phase fitting gave a period of 6.454835$\pm$0.000001 s. As in previous observations of 1E 1048.1−5937 , the folded light curve has a single broad peak of nearly sinusoidal shape. We fitted the background subtracted folded light curve with a constant (C) plus a sinusoid of amplitude A. The pulsed fraction, defined as A/C has values of 46.2$\pm$0.6% and 56.3$\pm$0.4%, respectively in the 0.6-1.5 keV and 1.5-10 keV ranges. These values are significantly smaller than those observed previously from this source ($\gtrsim$70%). In particular, the corresponding values during the 2000 December *XMM-Newton* observation are 76$\pm$4% and 96$\pm$2%. The time variation of the source pulsed fraction is illustrated in Fig. 1.

The reduced pulsed fraction, coupled with a larger overall flux, would suggest the presence of an additional, non-pulsed component in the 2003 observation. If this were the case,

the pulsed flux and spectrum should be the same in the two observations. We estimated the spectrum of the pulsed component of each observation from the difference between the total spectra and the spectra of the non-pulsed component. The latter were estimated from the phase interval corresponding to the pulse minimum, for a duration of 10% of the period. By fitting the resulting spectra with the blackbody plus power law model (Table 1) we found that the pulsed flux varied by $\sim$30% between the two observations. We thus conclude that a significant flux variation intervened also in the pulsed signal of the source.

2.2. *Chandra*

The *Chandra* satellite observed 1E 1048.1$-$5937 twice. The first observation was performed on 2001 July 4 using the High Resolution Camera (HRC-I) with the main objective of measuring with great accuracy the source position (Israel et al. 2002). The HRC-I does not provide spectral information. Assuming the same spectrum as the 2003 *XMM-Newton* observation, the measured count rate of 0.169 ± 0.005 counts s^{-1} corresponds to a 2-10 keV observed flux of $\sim3\times10^{-12}$ erg cm^{-2} s^{-1}. We performed a timing analysis as described in Israel et al. (2002) determining a best period P=6.45277 ± 0.00007 s. This value supersedes that of Israel et al. (2002), which was affected by an error in the program used for the Solar System Barycenter correction. The pulsed fraction, defined as described above, is 91 ± 3%.

The second *Chandra* observation was done using the ACIS instrument in High Energy Transmission Grating (HETG) mode on 2002 August 27-28, for an exposure time of 29,000 s. The data were processed using CIAO version 2.3. We applied a standard spatial filter and an order-sorting mask to extract the first–order events. The exposure map and effective area files were calculated taking into account the dithering of the satellite, and the spectrum (summed over ±1 orders) was corrected for the effective area, background subtracted and rebinned so as to have at least eighty photons per bin. These data have a time resolution of 3.24 s which does not allow us to derive a precise period value or to perform phase-resolved spectroscopy. The phase integrated spectrum was well described by the absorbed blackbody plus power law model with the best fit parameters reported in Table 1. The corresponding flux of $\sim 2\times10^{-11}$ ergs^{-2} s^{-1}, a factor of two larger than that of the 2003 *XMM-Newton* observation, is the highest ever observed from this source.

3. Discussion

All flux and period measurements of 1E 1048.1−5937 obtained in the last 11.5 years with imaging X–ray instruments are plotted as a function of time in Fig. 2. They indicate that, until the 2001 *Chandra* observation, the flux remained at a relatively stable level corresponding to a luminosity of $\sim 10^{34}$ erg s^{-1} (for d=5 kpc). Comparison of the two *XMM-Newton* flux values, which are unaffected by cross-calibration uncertainties related to the use of different detectors and have small statistical errors, provides unequivocal evidence for an increased luminosity. Furthermore, the data from the 2002 *Chandra* pointing suggests that we might have observed the decaying part of an outburst.

The most recent period value obtained with *XMM-Newton* lies above the extrapolation of the average spin-down of $\sim 2\times10^{-11}$ s s^{-1} observed in 1996-2001 (Fig.2 bottom, dotted line). This implies either a period of increased spin-down rate ($\dot{P} > 3.3\times10^{-11}$ s s^{-1}) or a sudden discontinuity (ΔP/P$\sim 10^{-4}$) after the 2001 July *Chandra* observation. Such a high spin-down rate has been seen on other occasions from this source (e.g. Mereghetti (1995)), while in the case of a sudden period variation, the sign is opposite to what is seen in radio pulsar glitches (which typically involve much smaller fractional variations). We note that a similar *antiglitch* probably occurred in SGR 1900+14 after the giant flare of 1998 August 27 (Woods et al. 1999; Palmer 2002).

We cannot rule out that the changes we observed in 1E 1048.1−5937 are related to the two short bursts detected in the fall of 2001 (Gavriil et al. 2002; the time of the bursts is indicated by the vertical line in Fig.2). In this respect it is interesting to compare our results with the properties of 1E 2259+586 , the other AXP that showed short bursting activity (Kaspi et al. 2003, Woods et al. 2003). 1E 2259+586 emitted more than 80 short bursts in 2002 June. They were much more similar to those of SGRs than the two bursts seen in 1E 1048.1−5937 , although their peak luminosity of (1-400)$\times10^{36}$ erg s^{-1} (2-10 keV, assuming isotropic emission and d=3 kpc, Kaspi et al. 2003) did not reach the largely super-Eddington values seen in bursts from SGRs. The onset of bursting activity in 1E 2259+586 was accompanied by an order of magnitude increase of the X–ray flux and a large glitch ($\Delta\nu/\nu = 4\times10^{-6}$). The subsequent flux decay, after a steep initial phase, was rather slow, reaching the pre-burst level after about one year. The spin-down rate for the first weeks after the glitch was about a factor 2 larger than the pre-glitch value, leading to a partial recovery of the frequency jump, but the following long term spin-down rate was only 2% *smaller* than before the glitch.

Although the 1E 1048.1−5937 data shown in Fig. 2 (top) are rather sparse, the flux evolution after the bursts is broadly consistent with that of 1E 2259+586 . However, the sign of the putative glitch and the long term spin-down torque indicate significant differences in

the frequency evolution of these two sources. Furthermore, our preliminary timing analysis of public data from the *Rossi-XTE* satellite does not provide evidence for any major timing discontinuity after the time of the 1E 1048.1−5937 bursts. Another difference is the long lasting change in the pulse profile of 1E 1048.1−5937 . Such a large variation in the pulsed fraction is the first observed in this source, and if it originated at the time of the bursts, it persisted for at least 1.5 year. For comparison, in 1E 2259+586 the variations in the pulse profile were recovered within about two months from the bursts (Woods et al. 2004).

Luminosity variations are commonly seen in accreting sources and generally explained as due to changes in the mass accretion rate, while under the magnetar hypothesis long lasting flux enhancements are typically related to the onset of crust fractures. For instance, twists in the external magnetic field induced by large scale fractures of the crust can force a persistent thermoionic current through the magnetosphere (Thompson et al. 2000). As a consequence, ions are lifted off the surface of the neutron star by their thermal motion, and the counterstreaming electrons are electrostatically accelerated to bulk relativistic speeds. The work done on electrons is then released in the form of Comptonized thermal photons, with a luminosity $L_X \approx 3 \times 10^{35} \theta A/Z(B/10B_{qed})$ ergs s^{-1}, where θ is the twist angle and B_{qed} $\sim$4.4$\times$10^{13} G. The resulting steady output in particles has been proposed to explain the factor 2-3 increase in the persistent X–ray flux of SGR 1900+14 after the event of 1998 August 27 (Thompson et al. 2000), and in an analogous way it may explain an increase of a factor of 4 in the luminosity of 1E 1048.1−5937 . Since the latter corresponds to $\sim$3$\times$10^{34} ergs s^{-1}, if B$\sim$B$_{qed}$ the required twist angle is $\lesssim$ 1 rad. If the flux increase is due to a static twist in the surface magnetic field, this will not necessarily be associated to the substantial increase observed in the torque, since the current flow is contained well inside the Alfvén radius. However, the enhanced spin-down may be induced by an increase in crustal fractures and variation in the rate of fractures induced by persistent seismic activity, the same mechanism responsible of the high timing noise during outburst-free epochs.

An alternative possibility, which accounts for both spin-down and luminosity, is the episodic onset of a wind (Duncan 2000). In this scenario, frequent small scale fractures in the crust produce quasi-steady seismic and magnetic vibrations, energize the magnetosphere and drive a diffuse, relativistic outflow of particles and Alfvén waves. The resulting wind luminosity, L_W, is proportional to the magnetic energy density in the deep crust, i.e. $\propto$B$^2_{crust}$, with the onset of the wind being possible only for $B_{crust} < (4\pi\mu)^{1/2} \sim 6 \times 10^{15}$ G, where μ is the shear modulus in the deep crust. For stronger fields, evolving magnetic stresses overwhelm lattice stresses and the crust deforms plastically instead of fracturing, turning off the Alfvén wind. In principle, this gives an upper limit $L_W \lesssim 5 \times 10^{36}$ ergs s^{-1}. In reality, as noted by Duncan (2000), magnetar winds must be mild enough to produce no detectable radio emission, and L_W is most likely comparable to the steady X–ray luminosity L_X emitted

by the hot stellar surface. When the persistent luminosity of the source, $L = L_X + L_W$ exceeds the magnetic dipole luminosity L_{mdr} as calculated from the stellar dipole field and angular velocity, the spin down torque grows by a factor of $\sim (L_/L_{mdr})^{1/2}$. In this contest, an episodic increase of a factor ~ 4 in luminosity could mean the spin down rate increased by a factor ~ 2 (Duncan 2000), as observed here. The episodic onset of a non-pulsed wind component can also account for the decrease in the pulse fraction. However, we found difficult to reconcile this scenario with the spectral invariance since there is no a priori reason why the spectrum of the wind component should appear so similar to that of the persistent X–ray source.

In fact, the 1E 1048.1−5937 spectrum remained unchanged despite the large variations of the flux and pulsed fraction. As shown above, the flux difference between the two *XMM-Newton* observations cannot be ascribed only to the variation of the non-pulsed component. Furthermore, the spectral invariance indicates that the unpulsed flux is not distinguishable, from the spectral point of view, from the pulsed one. In other words, both the pulsed and non-pulsed components are fitted by the same blackbody plus power law model. This supports the idea that the blackbody and power law spectral components of AXPs do not represent physically distinct emission processes, as was already suggested by the small energy dependence of the AXP pulsed fractions (Özel et al. 2001). A possibility is that the emission is of a thermal nature and the power-law in the fit simply reflects the inadequacy of describing a complex neutron star atmosphere with a simple blackbody model. The luminosity variation could be attributed to an increase in the area of the emitting surface, rather than to a temperature variation; this would also explain the reduction in pulsed fraction.

4. Conclusions

The data reported here provide solid evidence for long term variations in the flux and pulsed fraction of the AXP 1E 1048.1−5937 . Independently of the model adopted to explain the X–ray emission, the spectral invariance argues against the presence of two physically distinct spectral components.

The sparse coverage of the data does not permit us to unambiguously relate the observed variations to the two bursts seen in the fall of 2001. Furthermore, the differences with respect to the behavior of 1E 2259+586 after the 2002 June outburst suggest that the flux variations in 1E 1048.1−5937 are not necessarily related to SGR-like activity.

Long term flux variations have been reported for the AXP candidate AX J1845.0–0300 (Vasisht et al. 2000) and for the latest discovered member of the AXP class, XTE J1810−197 (Ibrahim et al. 2003, Gotthelf et al. 2004). The latter source was first seen in a bright state

(F$\sim 6 \times 10^{-11}$erg cm^{-2} s^{-1}, 2-10 keV) at the beginning of 2003. Its flux then decreased by a factor $\sim$3 in the first half of 2003. Archival data from ROSAT and ASCA, in which XTE J1810$-$197 was two orders of magnitude fainter, indicate that this source behaves like a transient. Interestingly, XTE J1810$-$197 is quite similar to 1E 1048.1$-$5937 also because of its spectral parameters, nearly sinusoidal pulse profile with a large pulsed fraction, spin-down at $\sim 10^{-11}$ s s^{-1} with considerable timing noise, and IR counterpart (Israel et al. 2004).

These observations suggest that luminosity variations in AXPs are more common than previously thought and not necessarily associated with the emission of energetic flares as in the classical SGRs.

This work has been partially supported by the Italian Space Agency. Based on observations with *XMM-Newton* , an ESA science mission with instruments and contributions directly funded by ESA member states and USA.

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Table 1: *Results spectral fits*

	Absorption (10^{22} cm^{-2})	Photon index	kT (keV)	$R_{BB}^{(a)}$ (km)	$F_{PL}^{(b)}$	$F^{(c)}$
2003 Jan	1.11±0.02	3.32±0.05	0.630±0.007	1.28±0.03	5.0±0.3	10.1±0.4
2000 Dec$^{(d)}$	0.96±0.09	2.9±0.2	0.63±0.04	0.8±0.1	2.8±0.8	4.7±0.3
2003 Jun$^{(e)}$	1.1±0.1	3.2±0.2	0.67±0.03	0.9±0.1	2.9±0.9	6.2±0.5
2000 Dec$^{(e)}$	1.0±0.3	2.9±0.7	0.61±0.07	0.8±0.3	2.3±2.0	4.1±0.3
2002 Aug$^{(f)}$	1.11 (fixed)	$2.7^{+1.6}_{-0.7}$	0.62±0.07	$2.1^{+0.7}_{-0.4}$	9±1	22±2

All errors are at the 90% confidence level for a single interesting parameter

[a] Radius at infinity for an assumed distance of 5 kpc.

[b] Observed flux of the power law component in units of 10^{-12} erg cm^{-2} s^{-1} (2-10 keV)

[c] Total flux (2-10 keV) in units of 10^{-12} erg cm^{-2} s^{-1}

[d] These values supersede the ones reported in Tiengo et al. (2002)

[e] Pulsed flux only

[f] *Chandra* HETG observation

Fig. 1.— Folded light curves (0.6-10 keV, EPIC PN) of 1E 1048.1−5937 during the December 2000 (left) and June 2003 (right) observations. The corresponding pulsed fractions (see text for definition) are 89%±1% and 52.8%±0.3%.

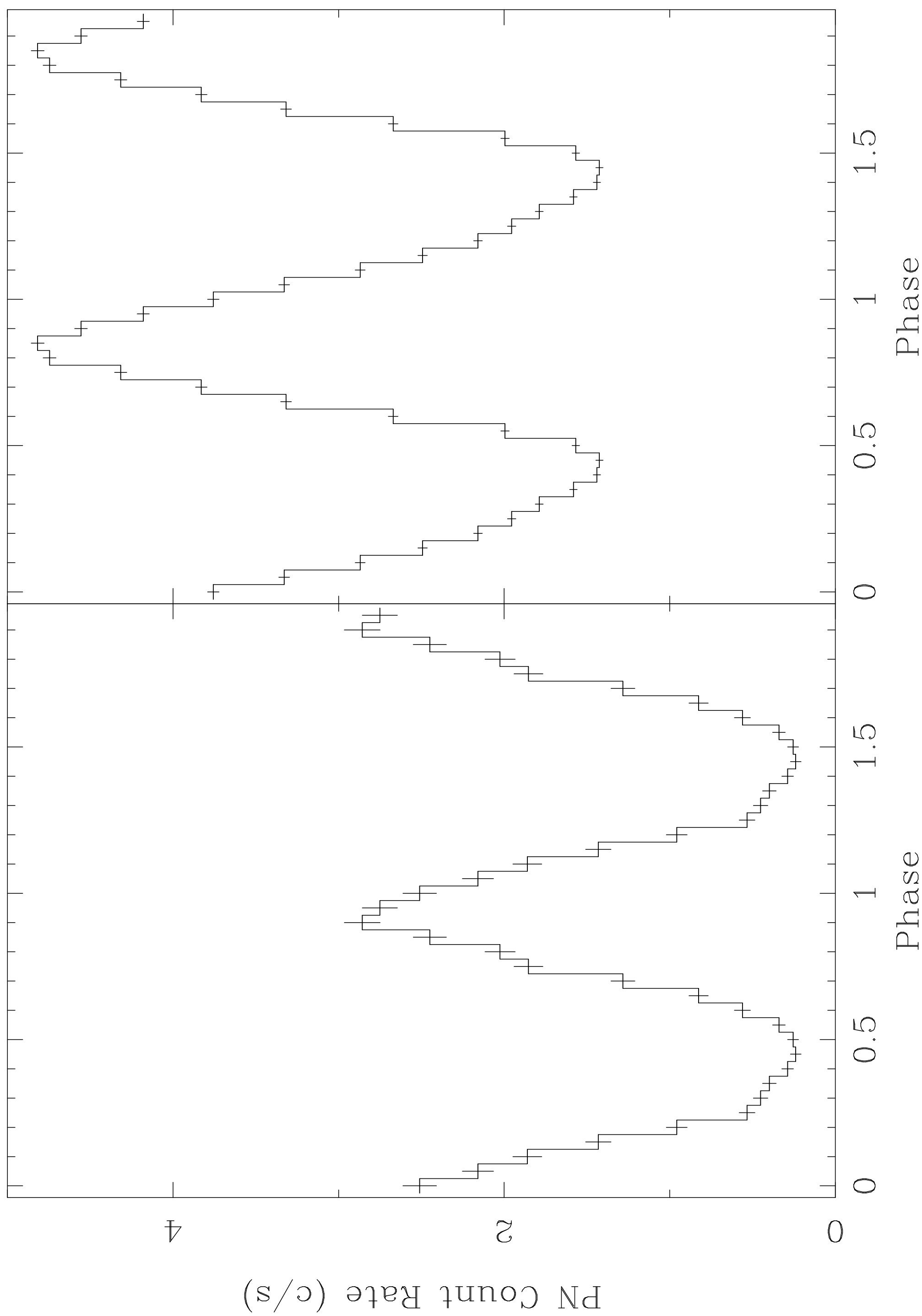
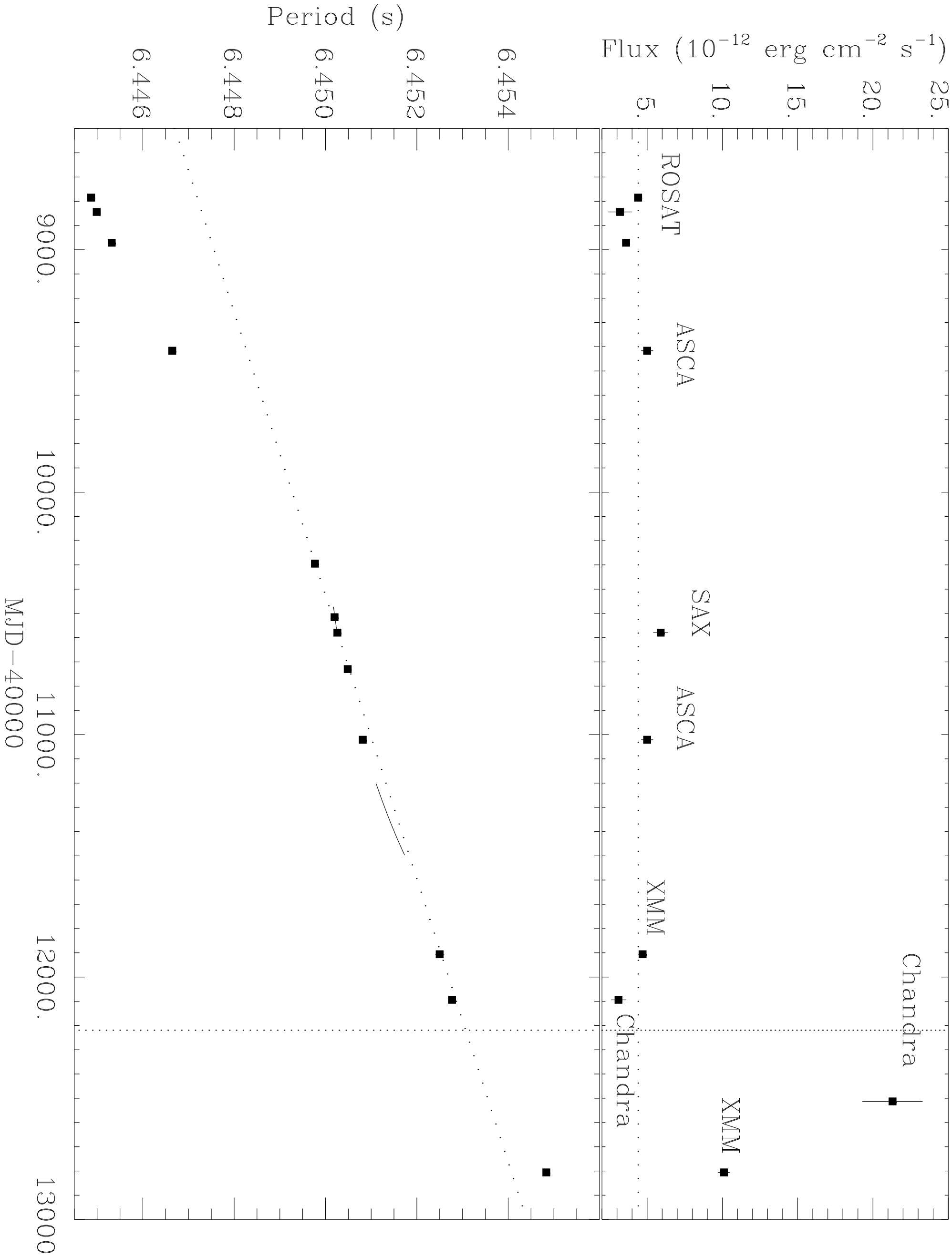


Fig. 2.— Flux and period history of 1E 1048.1−5937 . The vertical dotted line indicates the time of the bursts seen with *Rossi-XTE* . Top panel: Observed flux in the 2-10 keV range. Only measurements with imaging instruments are included. To derive the first four values, we re-analyzed the ROSAT data and converted the corresponding 0.6-2.4 keV fluxes to the 2-10 keV range by assuming the same spectral parameters as the 2000 *XMM-Newton* observation. The horizontal line is a fit with a constant, excluding the last two points. Bottom panel: Spin period evolution. The points without a corresponding one in the top panel are from *Rossi-XTE* . The solid line segments show two phase-coherent solutions from Kaspi et al. (2001).


Flux (10^{-12} erg cm^{-2} s^{-1})
5.
10.
15.
20.
25.
ROSAT
ASCA
SAX
ASCA
XMM
Chandra
Chandra
XMM
Period (s)
6.446
6.448
6.450
6.452
6.454
9000.
10000.
11000.
12000.
13000.
MJD−40000